Some Basic GN&C Modeling-and-Design Gap Areas for Low-Gee Slosh: Comparisons to Powered Flight Slosh

NASA Engineering and Safety Center (NESC)
Workshop on Low-Gee Slosh

22-23 Feb. 2023 at NASA/KSC

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Topics

Potential gaps between powered-flight slosh and near-zero-gee slosh modeling intuition …

- Extremely-basic items like inertia (which is a strong function of frequency and liquid depth)
- Visualization of response – ability to form a physical picture via mechanical analog
- Availability of frequency-domain design insight from open-loop plant
- Sense for edge-of model-validity – how does it behave “at the edges”

And some suggestions on how NASA can help

Selected References for Powered-Flight Slosh and Low-Gee Slosh

Primary Emphasis on Powered-Flight Slosh

1. NASA SP-106: Dynamic Behavior of Liquids, H. Norman Abramson, 1966. (“Old Testament”) – also includes some Low-Gee material
2. NASA TR R-187: Fluid Oscillations in the Container of a Space Vehicle and Their Influence Upon Stability, Helmut Bauer, 1964.
3. “Prediction of Liquid Slosh Damping Using a High-Resolution CFD Tool,” H. Q. Yang, John Peugeot and Jeff West, American Institute of Aeronautics and Astronautics; AIAA 2012-4294, 48th AIAA/ASME/SAE/ASEE Joint Propulsion Converence & Exhibit, 30 July-1 August 2012, Atlanta GA.
4. NASA CR-230, “Digital Analysis of Liquid Propellant Sloshing in Mobile Tanks with Rotational Symmetry,” by D. O. Lomen, published 1 May 1965.
5. AIAA 90-1878, Modeling of the Coupled Nonlinear Dynamics of Booster Vehicles, including Flexible Modes, Engines and Slosh, by Playter Elgersma and Morton

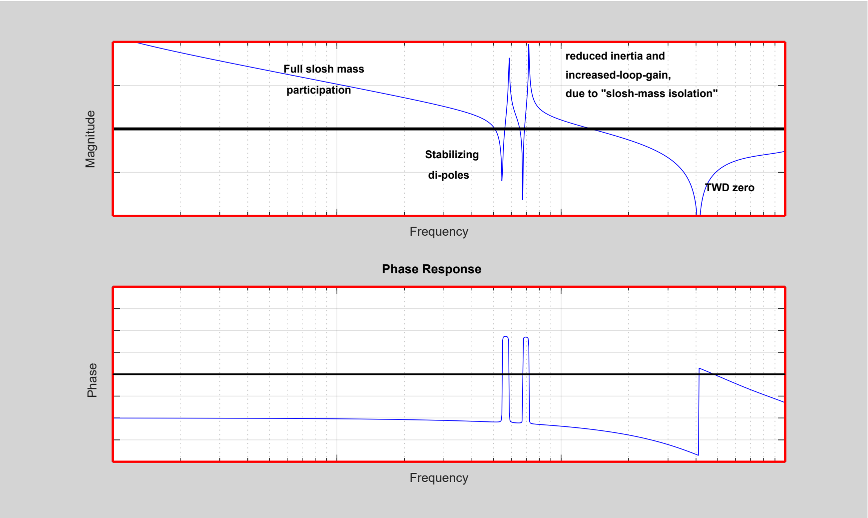
Strong Emphasis on LowGee or Zero Gee

1. The New Dynamic Behavior of Liquids in Moving Containers, Southwest Research Institute, 2000. (“New Testament” major update to SP-106 plus new material for lowGee slosh)
2. AIAA 2002-4845, Influence of the ATV Propellant Sloshing on the GNC Performance, by Baylor, L’Hullier, Ganet, Delpy, Francart and Paris
3. NASA TN-D-4132, “An experimental investigation of the frequency and viscous damping of liquids during weightlessness”, by Salzman, Labus and Masica, 1967
4. LR-TP-2005-518, “Measured states of Sloshsat FLEVO”, J.P.B. Vreeburg

Propellant Settling

1. Progress in Propulsion Physics 1 (2009) 293-304,“The United Launch Alliance Delta IV vehicle – an update to the pulse settling propellant management approach,”, by Berglund, Bassett, Mishic and Schrage

Possible Gaps Between Powered-Flight Slosh and Low Gee Slosh, for Insight into Plant Dynamics



🡐Open-loop plant <u>powered-flight</u> transfer function, TVC input to angular accel output for a generic launch vehicle

- Notional Params: m=1.5e5 kg; inertia 3e6; slosh masses 1e4kg
- Multiple frequency ranges of interest (and design insights):
  - **Nearly-zero frequency** – responds with 100% participation of all propellant except for fill fractions near h/D=1
  - **Near-slosh frequency** – responds as a tonal harmonic oscillator with strong coupling to vehicle, 2 dominant modes
    - And relative pole-zero dipoles provide key stability metrics
  - **Above-slosh frequency** – responds as a <u>lower-inertia</u> (several-db higher plant gain) system because slosh pendulums are 'mass isolated' – and the effect can be equivalent to a several-db increase in effective control power
  - <u>All</u> these regimes will affect the control gain and filtering choices
  - <u>All</u> the effects described above are well-understood across NASA and industry

- **Strong consensus across industry that this pendulum-or-spring/mass formulation is a valid, efficient framework for powered flight control design**
  - **Models (by now!) are easy to generate and are accurate; and they can rapidly provide a wealth of vehicle-specific <u>control design insights</u>**
  - **<u>And</u> there seems to be a consensus or common experience-base across industry, about what are effective slosh control <u>design strategies</u>**
- **Gaps for low-gee slosh:**
  - **Low-G version of above model is much harder to generate / validate; and validity ranges not as well-understood as for powered-flight**
  - **GNC does not have a large <u>common</u> experience base for low-gee plant-dynamics design insights, and effective control design strategies**

Modeling Gap: Powered-Flight Slosh Modeling vs Low-Gee Modeling in Low-Frequency Inertia as Function of Fill Height and Frequency

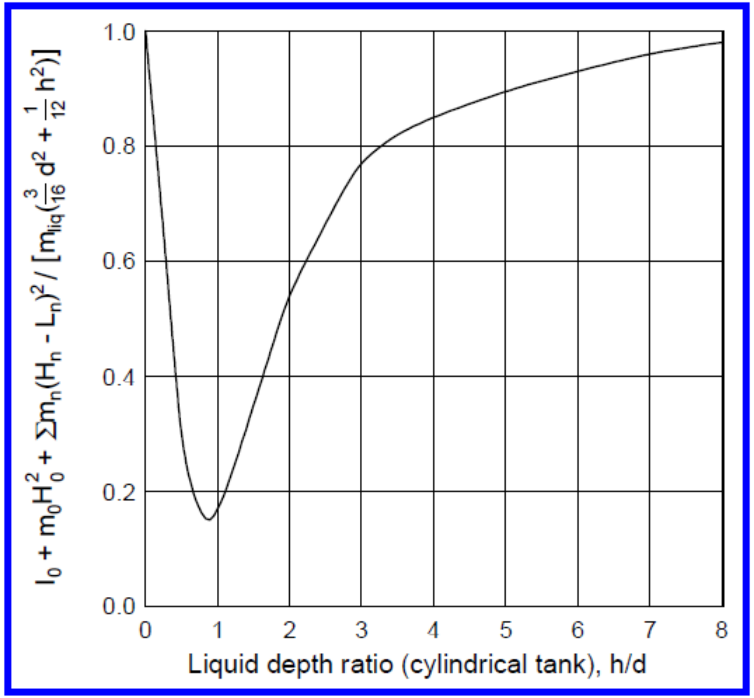


Figure 3.3. Ratio of model to frozen liquid moment of inertia for a cylindrical tank [Bauer, 1964]

- Figure at left is from SwRI Update of SP-106 (circa 2000)
- References the work of Bauer from 1964 (era of first version of SP-106)
- Plot show the ratio of the effective fluid inertia, to the frozen-fluid inertia, for a flat-bottom cylindrical tank – as a function of liquid depth ratio
- Frozen-inertia is the standard case – the self inertia of a cylinder **m*(d^2/4+h^2/12) -- all components contribute equally, at all frequencies**
- The effective low-frequency fluid inertia (below slosh mode frequency) includes multiple terms – non-sloshing point mass m0; non-sloshing "point inertia I0" and full participation of the slosh masses as well
- **Note, the effective inertia can be 5-10x lower than frozen inertia!** For spacecraft mass conditions of high fill level and fluid cg near system cg, the effect can significantly affect control power and control gain design.
- At frequencies above slosh modes, the effective inertia is reduced by the magnitude of the slosh mass contribution.
- This standard model has a lot of nuances! but there is broad GN&C consensus that it's a reasonable inertia description for powered flight slosh
- **Potential GAP: Is there any effective description available -- to guide the calculation of the (1/inertia) control effectiveness term and control gain design -- for zero-Gee slosh as a function of frequency and fill height?**

Excerpts from AIAA 2002-4845 – ATV Slosh Modeling, and Generation of GNC – One Instance of Validating a "GNC-centric" Model

Analysis of the docking phase

As the ATV motion during the docking phase is 6 d.o.f. controlled, typical acceleration profiles are made of pulses in all 6 d.o.f.. These pulses induce a linear mean acceleration that remains quite low (about 10^{-3} m/s²) and inconstant. Such acceleration profiles induce a slow motion of the liquid inside the tank, the fluid moving from one tank wall to another, without having a real pendulum-typed sloshing behavior.

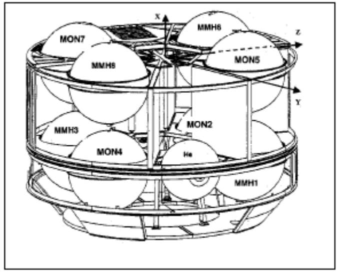


Figure 3 : ATV propellant tanks

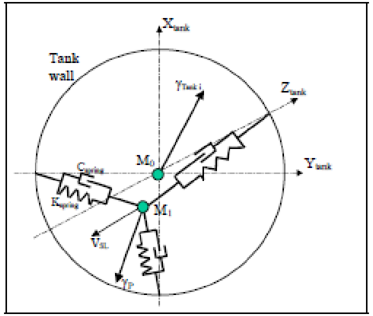


Figure 7 : Sloshing mechanical model for the docking phase

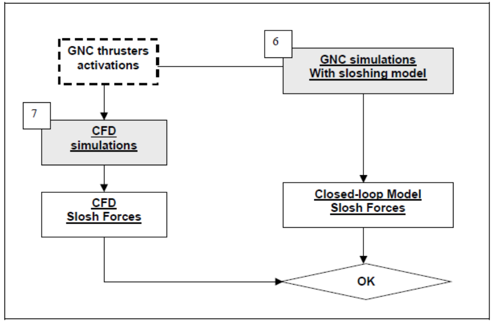


Figure 8 : Closed-loop validation logic

ATV program developed GNC-centric model using …

- Closed-loop GNC docking simulation with a simple spring-mass plant to generate total vehicle forces accelerations and rates
- Then applied the resulting kinematic conditions on a CFD model and calculated the resulting reaction forces from propellant
- Then iterated on the spring mass parameters until a good comparison between CFD forces and GNC model was achieved ➔
- **Excellent agreement was obtained with this approach! However …**
  - **Was not clear whether there is a <u>general</u> strategy available for the parameter iterations in the model validation validation**
  - **Still requires <u>significant</u> CFD utilization**
  - **GNC / CFD validation process would have to be repeated if configuration changed (like tank geom, or number of tanks)**
  - **<u>Process seems more suited to final verification, than to control design</u>**

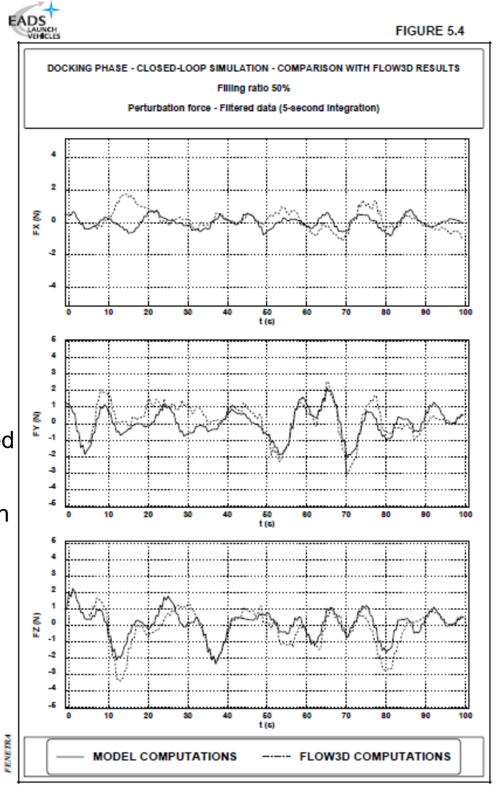


Figure 9 : FLOW3D / mechanical model compared results

Suggestions on “How Can NASA Help?”

- Gather or Develop examples of best-practices – for “GN&C-centric” **modeling** of low-gee slosh configurations – yielding low-order and efficient models (even if verified initially against CFD)
- Gather or Develop examples of best-practices – for closed-loop **control design** of low-gee slosh configurations

- Consider generating a Tech Bulletin which focuses on the limits of extrapolating the strong experience base of powered flight slosh mitigation, vs low Gee regime – addressing issues like below …
  - How do the two frameworks differ for high amplitude response?
  - How wide is the linear range for low-Gee slosh compared to powered slosh ? In other words, is the linear model range-of-validity a function of Bond number? What sorts of simulation dispersions are reasonable for very-low Bond number slosh mitigation?
  - Are pendulums or spring-mass systems even the best strategy for low-Gee low-order modeling?

- Consider generating a conference paper or Tech Bulletin which summarizes the applicability of on-orbit slosh testing to-date (sloshSat or Spheres for example) specifically to support low-order GNC-centric slosh modeling and control design
- Consider an NESC study to address the valid extrapolation ranges for the valuable NASA data base from drop-test experiments – extrapolating from “test tube scale, less than 25 mm radius” to tanks with several meter radius
- Provide some web-based resources like NESC Academy – possibly a family of animations from CFD -- for visualizing different regimes of low-gee slosh behavior to help develop intuition for dynamics and also illustrate difference between powered-flight slosh behavior and low-gee slosh behavior
- Consider whether the discipline of propellant-settling-burn design may be an under-utilized resource for low-Gee slosh modeling

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